1-1-2001

Influence of seed bank augmentation on performance of metolachlor

David Kariuki Kagima
Iowa State University

Influence of seed bank augmentation on performance of metolachlor

by

David Kariuki Kagima

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Crop Production and Physiology (Weed Science)

Program of Study Committee:
Robert G. Hartzler (Co-Major Professor)
Russell E. Mullen (Co-Major Professor)
Mark L. Gleason
James L. Baker

Iowa State University

Ames, Iowa

2001

Graduate College

Iowa State University

This is to certify that the Master's thesis of

David Kariuki Kagima

has met the thesis requirements of Iowa State University

Signatures have been redacted for privacy

DEDICATION

To my late mother

Miriam Wambui

and my late brother

David Karanja:

You always wanted me to succeed in life.

Thanks for your support.

And to my two lovely children

Andrew and Barbara:

Thanks for your love and patience.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

It is well established that pre-emergence herbicide activity is influenced by soil type, and recommended rates for most herbicides are adjusted to soil type. Current technology allows application rates to be adjusted on-the-go Variable Rate Application (VRA), adjusting the rate as soil type changes in a field. Most applicators offering this service base herbicide rates on soil organic matter content. However, several other factors influence herbicide activity, most importantly weed density and the environment (weather). This research was done to determine which of these factors was most important in determining the optimum herbicide rate, the benefit of VRA to the grower, and to determine the relative contribution of soil type, environment, and weed density to herbicide effectiveness.

Experimental areas were selected in Ogden, Nashua, Hinds and Bruner Farms based on differing soil types and environmental factors. The experiment was established as a split plot design in which micro-plots were established within main plots. Each micro-plot received different seedbank levels of giant foxtail seeds. Herbicide treatments were the main plot, with foxtail seed inputs as the split plot. Foxtail populations and biomass in the augmented micro-plots were significantly higher than micro-plots with the native populations. Increasing foxtail seed banks caused higher populations and biomass of weeds across all metolachlor treatments, while lower level seed banks maintained lower weed densities and biomass. Therefore, an increase in foxtail seed bank had a negative effect on herbicide efficacy. An increase in herbicide rate could not overcome the effect of higher foxtail populations.

Reduced efficacy at high seedbank densities could be explained by increased genetic

diversity within the weed population or a dilution of the herbicide by the increase in weed population. Greater weed diversity would increase resistance or tolerance, extension of period of emergence and the likelihood of weeds being in areas where they might not be contacted by herbicides. Increasing weed population could result in a sufficiently higher weed density that plants might not absorb lethal amounts of herbicide. It is documented elsewhere that increasing weed density resulted in a decrease in herbicide efficacy and data from this study was consistent with this report.

GENERAL INTRODUCTION

It is well established that pre-emergence herbicide activity is influenced by soil type, and recommended rates for most soil-applied herbicides are adjusted to soil type. Current technology allows application rates to be adjusted on the go (Variable Rate Application), adjusting the rate as soil type changes in a field. Most applicators offering this service base herbicide rates on soil organic matter content. However, several other factors influence herbicide activity, most importantly weed density and environment. This research was done to determine which of these factors are most important in determining the optimum herbicide rate, the benefit of VRA to the grower, and the relative contribution of soil type and weed density on herbicide effectiveness.

Thesis Organization

This thesis will be presented as a general literature review followed by materials and methods, results and discussion, a general conclusion, an appendix containing all applicable ANOVA tables, and a list of literature cited.

LITERATURE REVIEW

Precision agriculture was pioneered by the domestic United States industry, beginning with the conception and implementation of Variable-Rate Technology (VRT) (Precision Farming Guide, 1997). Precision farming has been labeled “farming by the foot.” The term implies that inputs can be varied on a square-foot basis. VRT applicators spatially vary the application rates of agricultural inputs such as seed, fertilizer, and crop protection chemicals. The equipment to perform variable-rate application (VRA) is commonly called variable-rate technology (VRT). Site-specific crop management (SSCM) is a term which more broadly describes the use of variability in soil and crop parameters to make decisions on the precise application of production inputs. VRA can be considered only one method of SSCM (Precision Farming Guide, 1997).

GPS, GIS and VRT

The U.S. Department of Defense (DOD) has built and deployed a constellation of satellites to support military operations worldwide. In 1993, the DOD implemented a policy of selective availability (SA) and making the global positioning system (GPS) available to the civilian community. The civilian community responded to SA by developing a differential system that eliminates SA error and increases positional accuracy from 2 to 5 m (Teske et al., 1996).

There are two options for implementing VRA: map-based VRA and sensor-based VRA. The map-based variable-rate application system, as the name suggests, adjusts the application rate of a product based on information contained in an electronic map of field properties. These systems must require the ability to determine machine position within the field and relate that position to a desired application rate by reading a map. Application rate is defined as the quantity of a product applied per unit area (kilograms per hectare). At the speeds that some applicator vehicles travel (25 kilometers per hour or more), looking ahead on the map for the next change in rate may be a function of an electronic controller. This look-ahead procedure takes into account the time required for the equipment to adjust a product flow rate after a decision is made to change the application rate (Precision Farming Guide, 1997). Map-based pesticide application utilizes map-based application controls for the application of both dry and liquid products. A map-stacking process is used to permit the proper selection and control of multiple fertilizer and herbicide products as an applicator travels through a field. The applicator control operating network monitors applicator speed and direction, measures spreading distance, sets application rates, monitors product bin levels, controls boom shut off, and monitors and informs the operator of application system status (Precision Guide for Agriculturists, 1997).

Sensor-based VRA uses data from real-time sensors instead of application rate maps to electronically control site-specific field operations. Real-time sensors operate on-the-go to measure soil properties or crop characteristics. VRA control systems then automatically use sensor data to match inputs such as fertilizer or herbicide to the need of soil and crops. Sensors must provide a continuous stream of data to the controller so that inputs can be varied over small areas throughout the field. This method of VRA does not necessarily require the use of a positioning system. However the sensors used for automatic applicator control can also be used for data collection. Thus, the sensor data, if recorded and geo-referenced, can be used in future SSCM or for creating control maps for other field operations (Precision Farming Guide, 1997). Sensor-based herbicide application is a current technology where soil organic matter (SOM) sensors are used for variable-rate application of a pre-plant herbicide. The amount of organic matter in the soil influences the effectiveness of some herbicides. Therefore, the manufacturer's labels sometimes recommend that users apply higher rates where more organic matter is present. Such a sensor could automatically adjust the herbicide rate based on SOM without additional data analysis or mapping. In this application, the sensor is pulled or pushed through the soil by the herbicide applicator rig. However, if sensor output is mapped, it could be used in future years to perform the same operation via map-based VRA (Precision Guide for Agriculturists, 1997). Commercially available sensors employed for VRT include those responsive to soil organic matter, cation exchange capacity (CEC), top soil depth, soil moisture, soil nitrate, and crop spectral reflectance (Committee on Assessing Crop Yield, 1997).

Sensors that successfully identify weeds against a background of soil are commercially available. It is much more difficult to identify weeds that are growing in the midst of a crop. Future application of VRT will develop sensors that successfully identify weeds by use of leaf shapes and colors to distinguish weeds from crops. This would help to bring VRT to post-emergence weed control. Coupling weed recognition sensors/systems with variable-rate applicators carrying multiple pesticides would allow true sensor-based, on-the-go weed control. When a particular weed is located and identified, the appropriate chemical could be applied to treat it (The Precision Farming Guide, 1997).

A recent sensor-based pesticide application is a weed seeker, which is primarily a selective spraying system for reducing postemergence herbicide usage. A reflectance sensor detects and identifies chlorophyll, using a light emitting diode (LED) light source. Electronics interpret the data and direct the operation of spray nozzle valves to apply chemical only where weeds are present based on light reflectance (The Precision Farming Guide, 1997).

The development of GPS, GIS and VRA equipment has made it possible to adjust herbicide rates as the sprayer goes across the field. Several custom applicators are now offering this service to farmers in Iowa. Most companies offering VRT adjust herbicide rates according to changes in SOM content across the field. Most preemergence herbicide labels take into account both soil texture and SOM in determining the recommended rate. From a metolachlor (Dual II Magnum) manufacturer label, base rate is set according to soil texture, and then an additional amount is added for each percentage change in SOM.

In herbicide application, VRT is aimed at maximizing profits by adjusting input levels in relation to some measurable factor. This method operates on the premise that not all areas of a field require the same level of herbicide inputs. When using this tactic, a producer would vary the rate of herbicide across the field. This is most often done according to soil type because of the availability of soil maps. Studies have revealed that the rate for 80% control with s-triazine herbicides was correlated with CEC values but negatively correlated with percent sand content (Suwanetnikom and Sattayanikom, 1991). Johnson et al. (1997) stated that the herbicide rate required to provide lethal concentrations in the soil varies by soil texture, SOM and pH. However, knowledge of other factors influencing the optimum rates for use with this tactic is limited.

Hartzler (1999) stated that there was value in adjusting herbicide rates according to changes in soil properties. However, the question arises of how much VRA is worth to the farmer. Other factors significantly influence the activity of preemergence herbicides, including the size of the weed seed bank and the environment. Adjusting herbicide rates to soil characteristics while ignoring other factors may reduce the value of VRA.

Weed populations are highly aggregated across most production fields. An important question for the present study is to answer which is more important in determining the optimum herbicide rate for a specific site, soil type or weed population. The value of adjusting herbicide rate according to soil type would be greatly diminished if weed population has a greater or equal impact to soil type in determining optimum herbicide rates. In many Iowa fields, there often is a strong correlation between SOM content of soils and weed populations. In these situations, increasing herbicide rates based on SOM would also compensate for increases in weed populations (Hartzler, 1999). However, in other fields there may be no correlation between soil type and weed populations. To gain the full benefit of VRA, it may be necessary to adjust herbicide rates in response to changes in both soil and weed populations (Hartzler, 1999).

Factors Influencing Efficacy of Pre-emergence Herbicides

Several physical and chemical factors affect activity of soil-applied herbicides. These factors include application method, time of application, volatility, adsorption, leaching, microbial and chemical degradation, and photodegradation.

Soil type

It is well documented that the performance of pre-emergence herbicides is strongly influenced by soil type. All herbicides are adsorbed to some degree to clay and organic matter, referred to as soil colloids. The portion of the herbicide adsorbed to soil colloids is not available to plants and does not immediately contribute to weed control. A significant portion of this product is eventually released into the soil solution where it is available to plants. Soils with high adsorptive capacity will require more herbicide to achieve effective control of weeds. Adjusting herbicide rates in response to changes in soil characteristics within a field is thus a reasonable approach (Hartzler, 1999).

Organic matter and clay particles are the primary sources of binding sites in the soil. In Iowa soils, the SOM fraction has a greater impact on soil adsorptivity than does clay (Hartzler, 1999). Researchers at North Carolina State University have shown that the herbicide rate required for effective weed control is strongly influenced by SOM, but the clay content or pH of the soil has little influence on herbicide efficacy (Baird et al., 1990).

Studies with several sulfonylurea herbicides found that both adsorption and herbicidal activity correlate more closely with soil humic matter (HM) than soil organic matter content (SOM) (Strek et al., 1995). Herbicide labels usually prescribe a range of rates corresponding to a range of SOM. The results of this study suggested basing herbicide rate recommendations on HM content rather than SOM content which may be of benefit to both farmers and soil testing laboratories (Strek et al., 1995). SOM is composed of a range of materials from plant and animal tissue through a host of temporary decomposition products to the fairly stable brown to black material defined as humus. The humic fraction accounts for the major herbicide-binding portion of several soil types. Humates account for as much as 90% of the total SOM in soil and are responsible for the brown to black color of many soils as well as most of the ionic exchange properties of the OM fraction (Strek et al., 1995).

In North Dakota, chlorsulfuron persistence in soil was greater in silty clay soils with pH 8.2 and 4.2% SOM than in loam soils with pH 6.2 and 2.2% organic matter. Loam soils with pH 6.0 and 1.5% SOM showed the least persistence (Ahrens et al., 1990). Research has indicated that imazethapyr may persist in soil for more than one year and carryover is greater in low pH soils than in high pH soils (Bresnahan et al., 1998). Research was carried out to determine imazethapyr adsorption-desorption in soils naturally varying with pH levels. Adsorption was greater at soil pH less than 6.0 compared to 7.5 or greater. (Bresnahan et al., 1998).

Miller and Westra (1996) reported that herbicide adsorption and desorption processes were largely responsible for herbicide behavior in the soils. The extent to which an herbicide is sorbed onto the soil solid-phase drives the ultimate fate of herbicides. Availability for plant uptake is thought to be profoundly controlled by soil sorption phenomena.

Field experiments were conducted on clay, silty loam and sand to study the influence of various soil parameters on s-trazine efficacy (Suwanketnikom et al., 1991). The average rate of herbicide required to achieve 80% weed control was in the order of clay>silty loam>sand. The efficacy of herbicides was negatively correlated with CEC values and positively correlated with % sand content. These results indicated that soil with high CEC value required a higher rate of s-triazines than soils with high sand content to obtain similar levels of weed control. Laboratory experiments in the same study indicated that adsorption of s-triazines was correlated with CEC values. The adsorption of atrazine and ametryn was correlated with clay, SOM content and CEC values, respectively, but negatively correlated with sand content. Shankle et al. (1998) have shown that fluometuron adsorption to soil was highly correlated with organic matter, sum of exchangeable cations, and clay content. An extension of the same study further observed that saturation by overflow increased half-lives of the active ingredient by 8 to 9 weeks. Correlation analysis of half-lives and soil properties indicated that there was a negative relationship with SOM, pH, clay and CEC, and a positive relationship with sand (Shankle et al., 1999). Raman et al. (1990) revealed that isoproturon and metoxuron adsorption on a soil humic acid increased with temperature.

Labels for most soil applied herbicides base rates on soil texture and organic matter content to compensate for differences in adsorption among soil types. Most growers set the herbicide rate for the average soil found in the field. This approach may result in parts of the field receiving more herbicide than necessary, whereas other areas may receive less than required. This misapplication of herbicide could result in crop injury, poor weed control, and off-target movement of herbicides (Hartzler, 1999).

Chemical factors and biodegradation

Biodegradation characteristics of imazaquin and imazethapyr were evaluated in Illinois by Cantwell et al. (1990). Herbicide degradation was compared on two soils, a Cisne silt loam with 14% sand, 74% silt, 12% clay, 1.3% SOM, and CEC of 12 meq/100g, and a Drummer silty clay loam with 9% sand, 57% silt, 34% clay, 5.8% SOM, and CEC of 40 meq/100g. Herbicide degradation in soil sterilized by gamma radiation sterilized was compared to fresh soil. After 12 weeks of incubation, imazaquin and imazethapyr degraded at a similar rate in unsterilized soil but both herbicides degraded slower in the Drummer soil. Herbicide adsorption was negatively correlated with degradation. Therefore, the amount of herbicide in soil solution as determined by soil characteristics will regulate microbial degradation (Cantwell et al., 1990).

A study was designed to investigate the relationship between chemical and microbial degradation of cyanazine and atrazine in four soils ranging in pH from 5.3 to 8.1 (Blumhorst et al., 1990). Generally the half-life of cyanazine decreased as the soil pH increased. Chemical hydrolysis was the primary means of atrazine degradation in a low pH soil. In a high pH soil, however, microbial degradation was the major factor involved in atrazine metabolism (Blumhorst et al., 1990).

Ajit et al. (1998) showed in their laboratory tests that triasulfuron and chlorsulfuron losses were much faster in non-sterile than sterile soils, demonstrating the importance of microbes in the breakdown of these herbicides, consequently influencing their efficacy.

Type of herbicide

Sorption and leaching potential of a herbicide affect efficacy. In general, weak acid herbicides are the least adsorbed whereas weak bases, non-polar and non-ionic herbicides are the most adsorbed (Oliveira et al., 1999). This aspect also influences the availability of herbicide in soil water solution for plant uptake.

Sulfonylurea herbicides are weak acids and pH greatly affects solubility and partitioning coefficient (Baird et al., 1990). As pH increases, their solubility increases, increasing their availability for plant uptake. Weak acid trapping reduces translocation, consequently reducing efficacy. Variation in soil pH that occurs within fields makes use of these chemicals difficult since they show variable response due to variability in soil type and herbicide solubility. Other studies with chlorimuron, a herbicide for soy beans and maize revealed that soil pH had little significance on its efficacy (Baird et al., 1990).

Environment

Herbicide degradation rates in soil greatly vary according to soil characteristics and environmental conditions. Degradation is influenced by soil type, pH, moisture content and other physiochemical factors. Rattanagreetakul et al. (1991) conducted laboratory studies on the effects of temperature and soil moisture on atrazine degradation. Atrazine solution was added to soil and incubated in controlled temperatures of 15, 25, 37 and 45C. The moisture content of the treated soil samples were maintained at 10, 30, 50, 100 or 150% of field capacity and soil was kept at room temperature. Soil samples were taken periodically and quantitative analysis of atrazine residues was determined by gas chromatography. Atrazine degradation was positively correlated with temperature and soil moisture.

Brian et al. (1999) also studied the effects of soil moisture and temperature on herbicide efficacy. Two temperature regimes were used, 25/23 C (day) and 5/3 C (night), and soil moisture was adjusted to one-third and full field capacity. Weed control was less at 5/3 C than at 25/23 C, and when soil moisture was at one-third field capacity, compared with full field capacity.

Renner (1998) stated that heavy rains reduce pre-emergence weed control. Efficacy of pre-emergence herbicides depend on the amount of rain, soil type, herbicide and weed species. Herbicides have the greatest tendency to be diluted within the soil profile on sandy soils. Loam soils, clay soils or soils with more clay and SOM will adsorb herbicides more than sandy soils and thus there will be less tendency for herbicides to leach. Weeds that germinate from a shallow depth such as annual grasses, pigweed, lambsquarters, mustard and common ragweed, have a tendency to survive if pre-emergence herbicides are leached by heavy rains.

Cultural practices

Brix-Davis and Clay (1996) stated that primary tillage may influence herbicide efficacy as well as chemical transport. Studies in Texas on clay loam soils have shown that cultural practices affect herbicide persistence in soil thus influencing herbicide performance. Sprinkler irrigation immediately after application reduced persistence of the three herbicides used (chlorosulfuron, sulfometuron and atrazine) compared to rain that fell 6 weeks later. Incorporation tended to reduce persistence and leaching was enhanced (Warner et al., 1990).

Tillage may influence herbicide effectiveness by altering the distribution of the seedbank within the soil profile. Production systems with intensive tillage distribute weed seeds throughout the plow depth, whereas in reduced till, new weed seeds remain near the soil surface (Pareja et al., 1985). Other field studies were conducted to evaluate effects of subsoiling and conventional tillage systems on imazaquin. Results indicated that concentration of the herbicide in the upper and lower layers of soil was not influenced by tillage system. Tillage system did not affect the amount of herbicide adsorbed on soil particles. Upper soil layers had a higher concentration of imazaquin than lower ones, irrespective of tillage system (Seirt et al., 1999).

Weed density

Winkle et al. (1981) reported that with increasing weed density, there was a decrease in herbicide activity. While working on oilseed rape *(Brassica napus)* in winter wheat in the UK, Kim et al. (1997) showed that weed density influenced the outcome of herbicide application. At low weed densities, lower doses of herbicide were effective in maintaining weeds below the economic threshold level.

The seed bank is a dynamic system. There is no perfect weed management system that ensures total eradication of weeds. Even a combination of tactics rarely provides complete control. Based on these escapes, there is a continued replenishment of the seed bank, ensuring weeds will be present in subsequent years. A study in Nebraska by Burnside et al. (1986) reported the seed bank size was diminished by up to 95% following complete control for six years. It was also reported that one year after control measures were stopped, the seed bank returned to 90% of its original size. Hartzler (1996) reported that a single velvetleaf plant could increase populations by 145 seedlings per plant in the subsequent year and by 203 seedlings per plant in the second year after seed production. Campbell and Thill (1996) reported that reduced herbicide doses often control weeds adequately and maintain crop yield in the short term. However, long-term weed management can be affected by seed production.

Buhler (1999) reported that weed control practices that maintained weed populations below yield reducing levels for a five-year period did not result in weed densities that were high enough to reduce control efficacy in succeeding years. If the field was kept weed-free for four years, weed densities were greatly reduced, but some weeds remained to reduce yields by 22% or more.

Hartzler and Roth (1993) reported that field history influenced the effectiveness of herbicide programs. They reported that the control of giant foxtail varied from 76 to 95% with 0 and 100% control in the preceding year respectively. This indicates that an increase in seed bank size can cause significant future problems. They further demonstrated that herbicides generally were more effective in conventional tillage than in no-tillage. In no-tillage, giant foxtail control in 1990 averaged 59% following 100% control in 1989, compared to 15% following 0% weed control. They went on to state that growers frequently report reduced herbicide effectiveness in years following weed control failures. This problem is more frequently observed in no-tillage production.

Taylor (1998) studied the effect of seed bank size on herbicide efficacy in corn, and reported that the addition of velvetleaf or giant foxtail seed to the seedbank had a negative impact on herbicide efficacy. This could be a result of increased diversity within the weed population or a dilution of the herbicide by the increase in weed population. Greater diversity would increase the likelihood of resistant or tolerant plants being present, expand the period of emergence, and increase the likelihood of weeds being in areas where they might not be contacted by herbicides. An increase in seed bank could also cause populations to become so dense that plants might not absorb lethal amounts of herbicide.

Weed species

Differential response of weed species and weed resistance to herbicides are widely documented. Cocklebur *(Xanthium strumarium)* was more responsive to herbicides followed by lambsquarters *(Chenopodium album)*, while sicklepod *(Cassia obtusifolia)* was least responsive (Guoying et al., 1996). Differential responses of species appeared to be related to the translocation and metabolism of prosulfuron.

Plant competition

Competitiveness of crop varieties may influence herbicide dose-response relationship. A field experiment by Kim et al. (1997) showed that two winter wheat cultivars with contrasting growth characteristics and different competitive ability had significant effects on herbicide performance in controlling oilseed rape. When reduced doses of herbicide were applied, the growth of weeds growing with a more competitive crop variety were suppressed more than that of weeds growing with a less competitive one.

Spatial variability of weeds

Rew et al. (1996) stated that distribution of weeds is rarely uniform or random. Weeds generally occur in clusters or patches. Current financial and environmental pressures on reducing herbicide inputs make field mapping and patch spraying an attractive proposition for farmers. Weed seeds and seedlings are spatially aggregated across agricultural landscapes despite the fact that fields are managed more or less uniformly (Johnson et al., 1996). The degree of spatial and temporal variation in weed populations is the result of many different types of interactions between plants and their environment. Changes in topography, soil type, and drainage patterns are apparent sources of variation within fields that may affect density and composition of the weed community.

Many reports show spatial variation in soil physical and chemical properties to which weeds and crops respond. Weed spatial heterogeneity results from variability in seed burial, germination, emergence, mortality, survival to maturity and subsequent seed production (Nadeau and King 1991). Herbicide rate could be varied in response to varying weed density or soil chemical and physical properties across a field. Forcella (1993) suggested that management of spatial variability is worthwhile as long as the amount of variability is large enough to justify the cost of obtaining information and managing these differences accordingly.

Specific associations of weed populations with soil physical and chemical characteristics have been observed. Experiments conducted in fields and greenhouses indicated that environments within habitat areas containing low soil organic matter typically had extremely low density of common sunflower, *Helianthus annuus* (Burton et al., 1999).

The Potential of Precision Agriculture to Improve Weed Management

In Alberta, Canada, site-specific spraying was carried out with clopyralid for control of Canada thistle. A 12.9 ha field was sprayed with a 102 g ai/ha average rate at a cost of $117.00 US/ha for a total cost of $1510.00. A typical broadcast application in the area is 201 g ai/ha to the whole field at a cost of $130.00 US/ha, equivalent to $1678.00 for the whole field. In the site-specific field, thistle control was satisfactory with few thistle occurrences not sprayed (Faechner and Hall, 1999).

The feasibility of site-specific spraying will depend on a number of factors and the long-term implications of this technology. Public pressure to reduce risk of herbicide contamination in food and water has illuminated the need to reduce herbicide use on agricultural lands. Moreover, the cost of herbicides has risen significantly over the last decade, increasing variable costs when profit margins are already small (Faechner and Hall, 1999). Nevertheless, producers worry about the long-term consequences of reduced herbicide use on future weed infestations and the risk of economically significant crop yield losses due to uncontrolled weeds (Faechner and Hall, 1999).

The characteristics of a weed infestation will influence the extent to which site-specific herbicide application is beneficial. Weeds tend to be more aggregated when population density is low and less aggregated when population densities are high (Johnson et al., 1995). Therefore, a field with low density may benefit more from site-specific weed management because a large portion of the field would not require herbicide application. Weed biology data also suggest that there is some stability in the pattern of weed aggregation over time. Weed aggregates occur in the same location for a period of time (Johnson et al., 1996). In general, long-lived seedbank species appear more stable than short-lived species, and populations are more stable in no-till than in conventionally tilled fields.

Analyses of weed populations in 12 Nebraska fields found that post-emergence herbicide applications could be reduced 71% for broadleaf weeds and 94% for grass weeds if only infested areas were treated (Johnson et al., 1997). Weed seedling density varied from 10 to 41 seedlings per meter of row length on fields with low to severe weed infestation. Associated crop losses varied from 20 to 43%. The authors estimate that herbicide use could be reduced 30 to 72% if real-time sensing and discrimination of weed species could be accomplished.

The use of real-time detection technology and sensor-activated sprayers may increase the selection pressure on weeds that escape preemergence herbicides. Care will have to be taken to limit the use of herbicides having the same mode of action in pre-emergence and post-emergence spot treatments in order to avoid herbicide resistance development. Increasing our understanding of the role of site-specific weed management will ultimately lead to more economically, environmentally and sociologically sustainable systems.

Site-specific weed management is a potentially powerful tool that can help to balance economic and environmental needs. Indeed, the main incentive to adopting site-specific weed management practices appears to stem from environmental benefits, which can be significant especially where weed pressure is low and distribution highly aggregated (Oriade, 1995). Site-specific weed management must go beyond just precision placement of chemical and non-chemical inputs. Site-specific management can help manage risk by providing information needed to optimize correct timing of inputs, determine and optimize relationships between biotic and abiotic variables and accurately monitor management successes and failures (Wallace, 1994). This aspect of site-specific management receives little attention due, in part, to a lack of understanding of spatial and temporal interactions between landscape characteristics (e.g., soil biophysical properties, slope, and aspect), pest populations, and weed management strategies. These factors lead to the objectives of this study.

MATERIALS AND METHODS

Experiments were conducted during the 1999 and 2000 seasons to evaluate the effect of soil type and seed bank density on herbicide performance.

1999 Season

In 1998, two experimental areas were selected based on differing SOM levels in a privately owned field near Ogden, Boone County, Iowa. The two sites were selected to represent the range of SOM content within the field. Soil properties were determined in each replication where samples were collected and evaluated at Nevada soil testing lab (Table 1).

Table 1. Soil characteristics at the two experimental sites, Ogden 1999.

Soil Sample	Soil pH	Buffer index	SOM (%)	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	CEC
Ogden 1	6.1	6.9	3.4	114.5	775	1550	270	13
Ogden 2	7.5	7.4	4.2	140.8	440	3625	362	22

The study was initiated on a previously well-managed site with low weed pressure. The experiment was established as a split plot design. Individual plot size was 2.4 m by 6.1 m, within an experimental area of 12.2 by 30.5 m. Three 1 m^2 micro-plots were established within each main plot to which seed treatments were added. Each 1 m^2 micro-plot received either no seed (A), 1,000 (B), or 4,000 giant foxtail seeds (C). Seeds were collected in the fall of 1998 from the ISU Curtiss Farm, Ames. Artificial seed banks were established in November 1998 for the 1999 study to allow seeds to overwinter under natural conditions. Plots were laid out as shown in Figure 1. Seeds were scattered onto the soil surface and

Rep 1	401 B C A R5	402 B A C R3	403 B A C R4	404 C B A R1	405 C A B R2
Rep 2	301 A B C R2	302 B C A R3	303 C B A R1	304 B C A R5	305 A B C R4
Rep 3	201 B C A R1	202 C A B R2	203 C A B R3	204 C B A R4	205 B A C R5
Rep 4	101 C B A R4	102 B C A R2	103 A C B R1	104 B C A R3	105 C A B R5

Figure 1. Experimental design for variable rate study. A, B and C represent micro-plots to which weed seed was added, and R1-R5 represent herbicide rates in each plot.

lightly raked into the soil. Herbicide treatments were the main plot, with foxtail seed inputs as the split plot. Each site had four replications with four rates of s-metolachlor[1] applied pre-emergence (1.3, 1.6, 1.9, and 2.2 kg/ha) and an untreated control. These rates encompass the range of rates recommended for the soils in the field selected for study. Herbicides were applied with a backpack sprayer equipped with 11002 Turbo jet nozzles. Both areas were planted with maize at an average density of 74,000 seeds/ha. Broadleaf weeds were controlled either by hand weeding or with a directed application of 0.45 kg/ha of bentazon[2].

[1] Dual II Magnum, Syngentia Crop Protection, Inc., Greensboro, NC 27419-8300.
[2] Basagran, BASF, Research Triangle Park, NC 27709.

Herbicide effects on maize were determined by gathering data on corn growth and development throughout the season. Data collected included weed counts and above-ground weed dry matter biomass. Weed counts within a 0.5 m square were initiated approximately four weeks after corn planting. Weed counts were taken at one-week intervals for 6 weeks followed by two-week intervals for a period of 4 weeks. Prior to corn harvest, all aboveground weed biomass was harvested, dried and then weighed. The week when weed population was highest was selected for analysis of weed densities at the end of season.

2000 Season

Three fields were selected for the 2000 experiments, located at ISU Hinds and Bruner Farms in Ames, and at Nashua. A similar experimental design as in 1999 was used. Three 0.5 m^2 micro-plots were established within each main plot and seed treatments added. Each 0.5 m^2 micro-plot received either no seed (A), 1000 (B), or 4000 giant foxtail seeds (C). The upper 2.5 cm of soil was placed in a bucket and seed thoroughly mixed in the soil before returning the mixture to the micro-plot. Foxtail seeds for all sites were collected from Curtiss Farm, Ames in the fall of 1999. The foxtail seeds were stored in a freezer until April 2000 when seed banks were established. Maize was planted and micro-plots established at Hind's Farm on April 20 and April 21, respectively, Bruner Farm on April 25 and April 27, and Nashua on May 2 and May 3. Herbicide treatments were the main plot, with foxtail seed inputs as the split plot. Each site had four replications with four rates of s-metolachlor applied preemergence (1.3, 1.6, 1.9, and 2.2 kg/ha) and an untreated control. These rates encompass the range of label rates recommended for VRA for the soils in the field selected for study. Herbicides were applied pre-emergence with a backpack sprayer equipped with

11002 Turbo jet nozzles. Overhead irrigation was used at the Hind's Farm on April 28 and on May 4 due to shortage of rainfall. Natural rainfall was not supplemented at the other two locations (Table 2). Soil properties at the three locations are listed in Table 3.

Herbicide effects on the maize crop were determined by gathering data on corn growth and development by measuring heights throughout the season. Data collected included weed counts and weed dry matter biomass. Weed counts within a 0.5 m^2 quadrant were initiated approximately one month after maize planting.

Table 2. Rainfall chart for Hind's, Nashua and Bruner Farms, and irrigation program for Hind's Farm between the months of April and May, 2000.

	Average weekly rainfall (cm)			Irrigation (cm)
	Nashua	Bruner	Hinds	Hinds
April 20 – 26	0.08	0.74	0.74	–
April 27 – May 3	0.03	0.05	0.05	3.81
May 4 – 10	1.17	0.38	0.38	1.90
May 11 – 17	0.66	0.18	0.18	–

Table 3. Soil characteristics at the three experimental sites, Hind's, Bruner, and Nashua Farms, 2000.

Soil Sample	Soil pH	Buffer index	SOM (%)	K (ppm)	P (ppm)	Ca (ppm)	Mg (ppm)	CEC
Hinds	6.1	7.2	2.6	150	80	1100	260	8
Bruner	6.3	6.9	4.5	250	82	1900	190	13
Nashua	6.8	7.1	4.1	100	58	1200	19-	8

These counts were taken at one-week intervals for 4 weeks followed by two-week intervals for another 4 weeks. The week when weed population was highest was selected and used for data analysis of weed densities. Prior to corn harvest, all above-ground weed biomass was harvested, dried and then weighed. Data were subjected to analysis of variance procedures in the SAS statistical application. Individual ANOVA tables are given in the Appendix. Treatment differences were determined by mean comparisons.

RESULTS AND DISCUSSION

1999 Experiments

There was no interaction between seedbank levels and herbicide rate treatments for either experimental area; thus, the data are pooled for main effects. There was a significant difference in weed density means among herbicide rates in both experiments. Higher rates of metolachlor provided better control of foxtail and reduced weed density compared with lower rates and the untreated control. There was no significant herbicide rate effect on biomass in the low SOM soil. On the high SOM soil however, weed biomass from the untreated plots was greater than on plots treated with metolachlor. Biomass in the control plots was 10 times greater in the high SOM soil than in the low SOM soil. The rate of herbicide applied did not affect weed biomass in the high SOM soil (Table 4).

Mean weed densities did not differ among the three artificial foxtail seedbank levels at either experimental area. Also, there was no significant seedbank effect on biomass in either experimental area (Table 5). Overall, the size of seedbank augmented did not have a significant effect on both weed density and biomass in the two experimental areas. The lack of response to seed bank augmentation may have been due to movement of seed during overwintering.

Table 4. Effect of metolachlor on weed density and biomass on two soil types within a field, 1999.[1]

Herbicide rate (kg/ha)	Low SOM Soil: Weed density (plants/m^2)	Low SOM Soil: Biomass (g/m^2)	High SOM Soil: Weed density (plants/m^2)	High SOM Soil: Biomass (g/m^2)
0	21a[2]	3.6a	23a	37.1a
1.3	14b	1.4a	13b	5.8b
1.6	8c	3.8a	11b	7.7b
1.9	6c	1.3a	6b	1.2b
2.2	5c	0.2a	7b	2.5b

[1]Means are pooled over three seedbank treatments.
[2]Means within a column followed by the same letter are not significantly different.

Table 5. Influence of seed bank augmentation on weed density and biomass on two soil types within a field, 1999.[1, 2]

Seedbank level (# seeds)	Low SOM Soil: Weed density (plants/m^2)	Low SOM Soil: Biomass (g/m^2)	High SOM soil: Weed density (plants/m^2)	High SOM soil: Biomass (g/m^2)
0	11a	2.5a	10a	8.0a
1000	10a	2.3a	12a	10.5ab
4000	11a	1.2a	13a	15.0b

[1]Means are pooled over five herbicide rates.
[2]Means within a column followed by the same letter are not significantly different.

2000 Experiments

A combined analysis of the three experiments showed a significant herbicide rate and seedbank effect (Table 6). Interactions were highly significant between field by herbicide, seedbank by herbicide, field by seedbank, and between field by seedbank by herbicide. However, analyzing data without the control herbicide rate showed that the herbicide rate effect disappeared (Table 7). Interactions between field by herbicide, seedbank by herbicide, and field by seedbank by herbicide also disappeared. Seedbank effect remained highly significant. Interactions between field by seedbank also remained significant.

Table 6. Combined analysis of the three experiments at the Hind's, Bruner and Nashua Farms, 2000.

Factor	Density	Biomass
	Pr>F	
Field	0.0003	<0.0001
Herbicide	<0.0001	<0.0001
Field*Herb	<0.0001	<0.0001
Seedbank	<0.0001	<0.0001
Seedb*Herb	<0.0001	<0.0001
Field*Seedb	0.02	<0.0001
F*S*H	<0.0001	<0.0001

Table 7. Combined analysis of the three experiments at the Hind's, Bruner and Nashua Farms without herbicide control, 2000.

Factor	Density	Biomass
	Pr>F	
Field	<0.0001	<0.0001
Herbicide	0.43	0.87
Field*Herb	0.67	0.49
Seedbank	<0.0001	<0.0001
Seedb*Herb	0.34	0.87
Field*Seedb	0.002	<0.0001
F*S*H	0.71	0.35

The analysis of variance (ANOVA) for the 2000 experiments for Hind's, Bruner and Nashua Farms are summarized in Table 8. There was a significant seedbank effect in all three experiments. Herbicide and seedbank interactions were highly significant at the Hind's and Nashua Farms. Herbicide effect was insignificant in all fields. Data were also analyzed

Table 8. Summary of ANOVA for Hinds, Bruner and Nashua Farms, 2000.

Factor	Hinds Farm Density	Hinds Farm Biomass	Bruner Farm Density	Bruner Farm Biomass	Nashua Farm Density	Nashua Farm Biomass
	Pr>F					
Herbicide	0.14	0.04	0.15	0.21	0.08	0.06
Seedbank	<0.0001	<0.0001	<0.0001	0.001	<0.0001	<0.0001
H*S	<0.0001	<0.0001	0.99	0.85	<0.0001	<0.0001

omitting the herbicide control in order to better evaluate differences among incremental rate changes. Data analysis without the herbicide control eliminated the interactions in the three experiments (Table 9). Seedbank effect remained significant and herbicide effect was not significant.

Table 9. Summary of ANOVA for Hind's, Bruner and Nashua Farms without herbicide control, 2000.

Factor	Hind's Farm Density	Hind's Farm Biomass	Brunner Farm Density	Brunner Farm Biomass	Nashua Farm Density	Nashua Farm Biomass
	Pr>F					
Herbicide	0.80	0.16	0.15	0.43	0.90	0.78
Seedbank	0.01	0.17	<0.0001	<0.001	<0.0001	0.01
H*S	0.85	0.82	0.07	0.34	0.98	0.80

Hinds Farm

In the untreated herbicide control, seedbank augmentation increased giant foxtail densities compared with the native seedbank (Figure 2). Giant foxtail densities of approximately 20 plant/m^2 were observed in plots without seedbank augmentation. Maximum giant foxtail densities of approximately 240 and 800 plants/m^2 occurred 8 weeks after

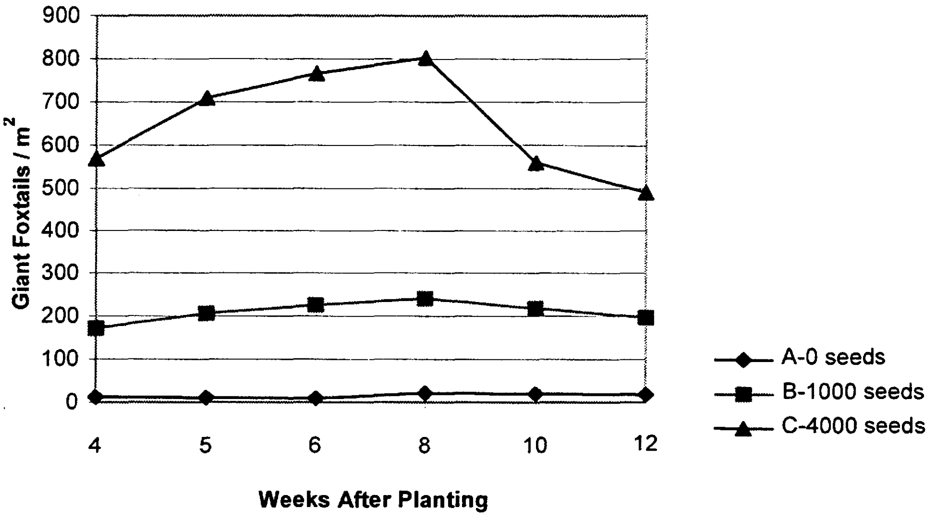

Figure 2. Effect of seedbank augmentation on giant foxtail density, Hinds Farm.

planting in the microplots with 1000 and 4000 seed/m^2 added, respectively. A large decrease in density occurred between 8 and 10 weeks in plots with 4000 seeds added to the seedbank. This self-thinning is commonly observed at high weed densities (Taylor, 1998).

A significant seedbank and herbicide*seedbank interaction occurred for both giant foxtail density and biomass, whereas the herbicide effect was significant only with biomass (Table 8). Analysis of data excluding the herbicide control treatment resulted in only the seedbank effect being significant (Table 9). This indicates that the herbicide and herbicide*seedbank interaction effects were due to large increases in foxtail densities in the control plots, with no difference in efficacy among the four herbicide rates.

Giant foxtail densities and biomass production was directly related to the foxtail seeding level averaged over the four herbicide rates (Table 10). Giant foxtail densities averaged 1 plant/m^2 in non-augmented plots, whereas the addition of 4000 seeds/m^2 resulted in greater than a 50-fold increase. Metolachlor reduced gaint foxtail densities and biomass by approximately 90% compared to the untreated control, but there were no differences among herbicide rates (Table 11). The number of weeds escaping control was directly related to the magnitude of the seedbank. The lack of an interaction between herbicide rate and seedbank augmentation indicates that increases in herbicide rate were unable to overcome the effect of the larger seedbank in augmented plots under these conditions.

Table 10. Influence of seedbank augmentation on weed density and biomass at the Hind's Farm (eight weeks after planting), 2000.[1,2]

Seedbank level (# seeds)	Weed density (plants/m^2)	Biomass (g/m^2)
0	1b	0.1a
1000	10b	0.1a
4000	65a	0.5a

[1]Means are pooled over five herbicide rates.
[2]Means within a column followed by the same letter are not significantly different.

Table 11. Effect of metolachlor on weed density and biomass at the Hind's Farm (eight weeks after planting), 2000.[1,2]

Herbicide rate (kg/ha)	Weed density (plants/m^2)	Biomass (g/m^2)
0	251	30.3
1.3	34a	0.5a
1.6	9a	0.1a
1.9	27a	0.0a
2.2	21a	0.1a

[1]Means are pooled over three seedbank treatments.
[2]Means within a column followed by the same letter are not significantly different.
[3]Data from herbicide control not included in analysis.

Bruner Farm

Seedbank augmentation increased weed densities in the untreated control compared with the native seedbank (Figure 3). Giant foxtail densities were very low in plots without seedbank augmentation. Maximum giant foxtail densities of approximately 160 and 280 plants/m^2 occurred seven weeks after planting in the microplots with 1000 and 4000 seed/m^2 added, respectively. Densities decreased by approximately 20% between 7 and 11 weeks in plots with 4000 seeds added to the seedbank.

A significant seedbank effect occurred in both giant foxtail density and biomass (Table 8). Analysis of data excluding the herbicide control treatment resulted in only the seedbank effect being significant (Table 9).

Giant foxtail densities and biomass production was directly related to the foxtail seeding level averaged over the four herbicide rates (Table 12). Giant foxtail density of

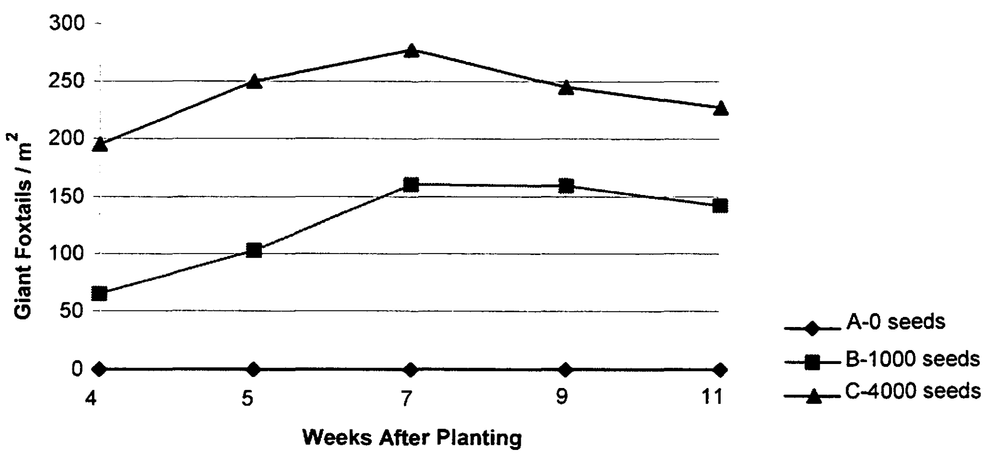

Figure 3. Effect of seedbank augmentation on giant foxtail densities, Bruner Farm.

Table 12. Influence of seedbank augmentation on weed density and biomass at the Bruner Farm, 2000.[1,2]

Seedbank level (# seeds)	Weed density (plants/m^2)	Biomass (g/m^2)
0	1c[2]	0.0b
1000	39b	10.7b
4000	161a	53.1a

[1]Means are pooled over five herbicide rates.
[2]Means within a column followed by the same letter are not significantly different.

1 plant/m^2 was observed in non-augmented plots, whereas the addition of 4000 seeds/m^2 resulted in 161 plants/m^2. Metolachlor reduced giant foxtail densities and biomass by approximately 6% relative to the untreated control, but there were no differences among herbicide rates (Table 13). The poor control was probably due to the lack of rainfall after application. The number of weeds escaping control was directly related to the magnitude of the seedbank. The lack of an interaction between herbicide rate and seedbank augmentation indicates that increases in herbicide rate was unable to overcome the effect of the larger seedbank in augmented plots under these conditions.

Table 13. Effect of metolachlor on weed density and biomass at the Bruner Farm, 2000.[1,2]

Herbicide rate (kg/ha)	Weed density[3] (plants/m^2)	Biomass (g/m^2)
0	22	18.3
0.4	11a	4.8a
1.6	32a	12.7a
1.9	20a	16.9a
2.2	20a	9.7a

[1]Means are pooled over three seedbank treatments.
[2]Means within a column followed by the same letter are not significantly different.
[3]Data from herbicide control not included in data analysis.

Nashua Farm

Seedbank augmentation increased weed densities in the untreated herbicide control compared to the native seedbank (Figure 4). Giant foxtail densities of less than one plant/m^2 were observed in plots without seedbank augmentation. Maximum giant foxtail densities of approximately 290 and 670 plants/m^2 occurred seven weeks after planting in the microplots with 1000 and 4000 seed/m^2 added, respectively. Densities decreased approximately 10% from 7 to 11 weeks after planting in plots with 4000 seeds added to the seedbank, whereas the decrease was less than 5% in plots with 1000 seeds added.

A significant seedbank and herbicide*seedbank interaction occurred in both giant foxtail density and biomass (Table 8). Analysis of data excluding the herbicide control treatment resulted in only the seedbank effect being significant (Table 9). This indicates that the herbicide*seedbank interaction effect was due to large increases in foxtail densities in the control plots, with no difference in efficacy among the four herbicide rates.

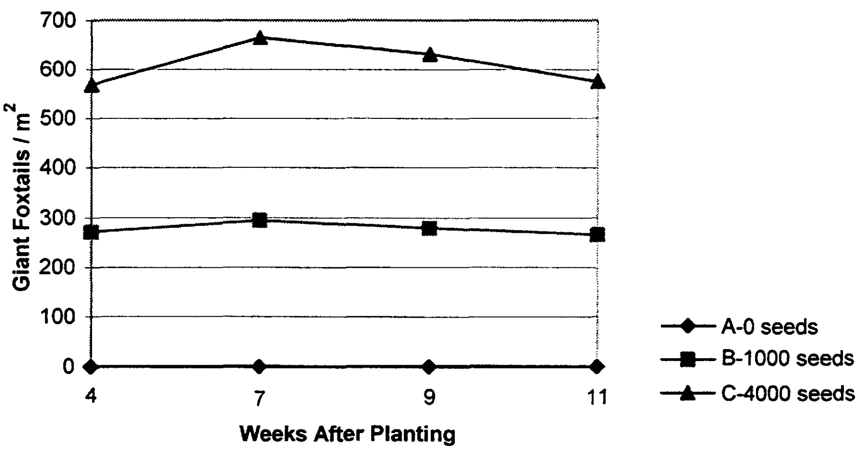

Figure 4. Effect of seedbank augmentation on giant foxtail densities, Nashua Farm.

Giant foxtail densities and biomass production was directly related to the foxtail seeding level averaged over the four herbicide rates (Table 14). Giant foxtail densities averaged 0 plant/m^2 in non-augmented plots, whereas the addition of 4000 seeds/m^2 resulted in a 250-fold increase. Metolachlor reduced giant foxtail densities and biomass by approximately 75% to the untreated control, but there were no differences among herbicide rates (Table 15). The number of weeds escaping control was directly related to the magnitude of the seedbank. The lack of an interaction between herbicide rate and seedbank augmentation indicates that increase in herbicide rate was unable to overcome the effect of the larger seedbank in augmented plots under these conditions.

Table 14. Influence of seedbank augmentation on weed density and biomass at the Nashua Farm, 2000.[1,2]

Seedbank level (# seeds)	Weed density (plants/m^2)	Biomass (g/m^2)
0	0c	0.0b
1000	47b	10.3ab
4000	156a	22.9a

[1]Means are pooled over five herbicide rates.
[2]Means within a column followed by the same letter are not significantly different.

Table 15. Effect of metolachlor on weed density and biomass at the Nashua Farm, 2000.[1,2]

Herbicide rate (kg/ha)	Weed density[3] (plants/m^2)	Biomass[3] (g/m^2)
0	280	106
1.3	99 a	34.0a
1.6	67a	17.5a
1.9	52a	17.6a
2.2	59a	15.9a

[1]Means are pooled over three seedbank treatments.
[2]Means within a column followed by the same letter are not significantly different.
[3]Data from herbicide control not included in analysis.

Overall, an increase in foxtail seedbank had a negative effect on herbicide efficacy. The increase in seedbank resulted in significantly higher populations and biomass and increases in herbicide rate did not overcome the effect of higher foxtail populations. Reduced efficacy could be explained by increased genetic diversity within the weed population or a dilution of the herbicide by the increase in weed population. Greater genetic diversity would increase the likelihood of resistance or tolerance, extension of period of emergence and increase the likelihood of weeds being in areas where they might not be contacted by herbicides. Increasing weed population could also result in sufficiently higher weed density so that plants might not absorb lethal amounts of herbicide. It is documented that increasing weed density resulted in a decrease in herbicide activity (Winkle et al., 1981).

At the three sites in the 2000 season, there was a significant seedbank effect, but no differences among herbicide rates. At Nashua and Hinds Farms, the herbicide (averaged over 4 rates) resulted in at least a 75% reduction in foxtail density and biomass compared to the untreated control. However, at Bruner Farm, the herbicide only reduced density by 10% and biomass by 40%. Although there are numerous differences among the sites, the timing of significant rainfall (irrigation) is probably the factor that led to the large differences in herbicide efficacy between the three sites. Both Hinds and Nashua Farms had significant rain (> 1.5 cm in the first 10 days after planting). This illustrates the importance of the environment in the performance of herbicides.

GENERAL CONCLUSIONS

The experiment was designed to determine the relative contribution of soil type, weed density and environmental differences on herbicide performance. Differences in SOM levels in most fields in Iowa are relatively small, but they may differ sufficiently to influence herbicide performance. Weed control was severely affected by higher weed densities at all sites. An increase in weed seedbank increased weed populations and reduced herbicide efficacy for most herbicide treatments. Good control was achieved at higher herbicide rates in native seedbanks at all sites.

Earlier studies by Taylor and Hartzler (1998) and Hartzler and Roth (1993) looked at the impact of seedbank size and herbicide effectiveness, and reported that increasing the intensity of management could overcome increases in seedbank size. The earlier studies evaluated a wider range of rates, using rates lower than likely to be used commercially. In this study, we evaluated the range of rates covered by the herbicide label and likely to be used in VRA. The studies showed that there is little value to making these small incremental changes in rates since other factors have a significant influence on herbicide performance. Metolachlor performance was poor at sites with low rainfall and better at sites with higher rainfall or irrigation. The data presented allowed us to conclude that weed density and weather have a significant impact on herbicide performance. There was little value in making small incremental changes in herbicide rates. Therefore, neglecting the environment and spatial pattern of weeds in a field will negate much of the benefit of VRA.

APPENDIX: ANOVA TABLES

1999 Season

Table 1. Analysis of variance for weed density in Ogden 2 (4.2% OM).

Source	DF	SS	Mean Square	F Value	Pr>F
herb	4	2066.56	516.64	0.64	0.56
seedb	2	76.30	38.15	1.02	0.37
herb*seedb	8	720.53	90.06	2.40	0.08

Table 2. Analysis of variance for biomass in Ogden 2 (4.2% OM).

Source	DF	SS	Mean Square	F Value	Pr>F
herb	4	10627	2556.64	41.64	<.0001
seedb	2	377.21	188.60	5.58	0.008
Seedb*herb	8	510.46	63.80	1.89	0.099

Table 3. Analysis of variance for weed density in Ogden 1 (3.4% OM).

Source	DF	SS	Mean Square	F Value	Pr>F
herb	4	1985.13	496.28	7.28	0.008
seedb	2	21.36	10.68	0.07	0.93
seedb*herb	8	545.46	68.18	0.44	0.889

Table 4. Analysis of variance for biomass in Ogden 1 (3.4% OM).

Source	DF	SS	Mean Square	F Value	Pr>F
herb	4	116.93	29.23	2.50	0.126
seedb	2	15.85	7.92	0.87	0.429
Seedb*herb	8	93.63	11.70	1.29	0.288

2000 Season

Table 5. Analysis of variance for weed density in Nashua (4.1% OM).

Source	DF	SS	Mean Square	F Value	Pr>F
herb	4	454299.5	113574.87	3.06	0.083
seedb	2	602292.4	301146.2	90.58	<0.0001
Seedb*herb	8	296753.6	37094.2	11.16	<0.0001

Table 6. Analysis of variance for biomass in Nashua (4.1% OM).

Source	DF	SS	Mean Square	F Value	Pr>F
herb	4	71559.4	17889.85	3.42	0.065
seedb	2	70869.6	35434.8	52.34	<0.0001
Seedb*herb	8	41823.13	5227.89	7.72	<0.0001

Table 7. Analysis of variance for weed density in Hind's Farm (2.6% OM).

Source	DF	SS	Mean Square	F Value	Pr>F
herb	4	492389.4	123099.6	2.36	0.14
seedb	2	286899.63	143449.81	31.36	<0.0001
Seedb*herb	8	417834.7	52229.33	11.42	<0.0001

Table 8. Analysis of variance for biomas in Hinds Farm (2.6% OM).

Source	DF	SS	Mean Square	F Value	Pr>F
herb	4	8717.46	2179.36	4.17	0.04
seedb	2	1138.22	569.11	33.01	<0.0001
Seedb*herb	8	4181.58	522.69	30.32	<0.0001

Table 9. Analysis of variance for weed density in Bruner Farm (4.5% OM).

Source	DF	SS	Mean Square	F Value	Pr>F
herb	4	4050.28	1012.57	2.26	0.152
seedb	2	279487.19	139743.59	58.68	<0.0001
Seedb*herb	8	3591.73	448.96	0.19	0.990

Table 10. Analysis of variance for biomas in Brunner Farm (4.5% OM).

Source	DF	SS	Mean Square	F Value	Pr>F
herb	4	1424.24	356.06	1.84	0.214
seedb	2	6596.87	3298.43	8.43	0.0012
Seedb*herb	8	1545.09	193.13	0.49	0.851

LITERATURE CITED

Ahrens, W. H., and D. G. Ouse. 1990. Chlorsulfuron degradation in a wheat-fallow rotation: Weed Sci. 8: 92.

Ajit K. S., R. S. Kookana, and A M. Alston. 1998. Degradation of two sulfonylurea herbicides in alkaline soils under laboratory conditions. Weed Sci. 12: 57.

Baird, D. L., E. L. Knake, and L. E. Paul. 1990. Effect of pH, tillage, and rate on residual effect of chlorimuron on corn: Weed Sci. 206: 91-92.

Bhuler, D. D. 1999. Residual effects of weed control practices on weed populations, control, and soybean *(Glycine max).* Proc. North Cent. Weed Sci. Soc. 39: 27.

Blumhorst, M. R., and J. B. Weber. 1990. Chemical versus microbial degradation of atrazine and cyanazine in soils. Weed Sci. 212: 94.

Bresnahan, G. A., A. G. Dexter, and W. C. Koskinen. 1998. Influence of soil pH on Imezathapyr adsorption and carryover. Weed Sci. 12: 57.

Brian L. S. Olson, Kassim Al-Khatib, P.W. Stahlman, S. K. Parrish, and P. J. Isakson. 1999. MON 37500 efficacy as affected by soil moisture and temperature. Proc. North Cent. Weed Sci. 39: 125-126.

Brix-Davis, K. A., and S. A. Clay. 1996. Atrazine and Alachlor placement and tillage impacts on weed competition, herbicide movement, and corn yield. Weed Sci. 215: 67.

Burton M. G., D. A. Mortensen, J. L. Lindquist, and A. R. Martin. 1999. The influence of soil characteristics and location on the fitness and control of common sunflower. Proc. North. Cent. Weed Sci. Soc. 39: 34.

Burnside, O. C., R. S. Moomaw, F. W. Roeth, G. A. Wicks, and R. G. Wilson. 1986. Weed seed demise in soil in weed free corn *(Zea Mays)* production across Nebraska. Weed Sci. 34: 248-251.

Cantwell, R. A., Liebel, and F. W. Slife. 1990. Biodegradation characteristics of imazaquin and imazethapyr: Weed Sci. 212: 93-94.

Campbell, J. M., and D. C. Thill. 1996. Air shear and conventional sprayer comparison of weed seed production and foliage coverage. Weed Sci. 212: 66-67.

Committee on Assessing Crop Yield. 1997. Precision Agriculture in the 21st Century. National Academy Press. Washington, D.C.

Faechner T. and L. M. Hall. 1999. Operational site-specific spraying. Proc. North Cent. Weed Sci. Soc. 39: 34-35.

Forcella, F. 1993. Value of managing within-field variability. ASA Misc. Public., ASA, CSSA, and SSSA, Madison, WI.

Guoying Ma, H. D. Coble, F. T. Corbin, and J. D. Burton. 1996. Differential responses of weed species to prosulfuron. Weed Sci. 36: 67.

Hartzler, R. G. 1999. Personal communication: ISU Weed Science.

Hartzler, R. G. 1996. Velvetleaf *(Abutilon theophrasti)* population dynamics following a single year's seed rain. Weed Tech. 10: 581-586.

Hartzler, R. G., and G. W. Roth. 1993. Effect of prior year's weed control on herbicide effectiveness in corn *(Zea mays)*. Weed Tech. 7: 611-614.

Johnson, G. A., Cardina, and D. A. Mortensen. 1997. Site specific weed management: Current and future directions. Pages 131-147 In The State of Site-Specific Management for Agriculture. Madison, WI.

Johnson, G. A., D. A. Mortensen, and C. A. Gotway. 1996. Spatial and temporal analysis of weed seedling populations using geostatistics. Proc. Weed Sci. 44: 704-710.

Johnson, G. A., D. A. Mortensen, and A. R. Martin. 1995. A simulation of herbicide use based on weed spatial distribution. Weed Res. 35: 197-205.

Kim, D. S., P. Brain, J. C. Caseley, and E. J. P. Marshall. 1997. IACR-Long Ashton Research Station, Department of Agricultural Sciences, University of Bristol, Long Ashton, Bristol BS18 9AF, UK.

Lasat, M. M., J. M. Ditomaso, J. J. Hart, and L. V. Kochian. 1996. Journal of European Weed Research Society.

Miller, P. A., and P. Westra. 1996. Correlation of soil adsorption with bioavailability for chloroacetamide herbicides in diverse soil types. Weed Sci. 196: 61.

Nadeau, L. B., and J. R. King. 1991. Seed dispersal and seedling establishment of *Linara vulgaris* Mill. Can. J. Plant. Sci. 71: 771-782.

Oliveira R. S., W. C. Koskinen, and F. A. Ferreira. 1999. Sorption and leaching potential of herbicides in the Brazilian soil. Proc. South. Weed Sci. Soc. 39: 46-47.

Oriade, C. 1995. A bioeconomic analysis of site-specific management and delayed planting strategies for weed control. Ph.D. dissertation, University of Minnesota, St. Paul.

Pareja, M. R., D. W. Stainforth, and G. P. Pareja. 1985. Distribution of weed seed among soil structural units. Weed Sci. 33: 182-189.

The Precision Farming Guide for Agriculturists. 1997. John Deere Publishing Department 374 John Deere Road, Moline, IL 61265-8098.

Raman, S. 1990. Thermodynamics of adsorption of isoproturon and metoxuron on soil humic acid. Weed Sci. 215: 95.

Rattagreetakul, C., R. Korpraditskul, and V. Korpraditskul. 1991. Effect of temperature and soil moisture on Atrazine degradation. Kasetsart Journal (Nat. Sci. Suppl.) Vol. 25: 75-79.

Renner, K. 1998. Field Crop CAT Alerts 1993-97-06139605. Michigan State University Extension.

Rew, L. J., G. W. Cussans, M. A. Mugglestone, and P. C. H. Miller. 1996. A technique for mapping the spatial distribution of *Elymus repens,* with estimates of the potential reduction in herbicide usage from patch spraying. Journal of European Weed Research Society. Vol.36: 283-292.

Seifert S., D. R. Shaw, M. boyette, W. L. Kingerly. 1999. Environmental fate of imazaquin in a sharky clay soil: effect of tillage systems. Proc. North Cent. Weed Sci. Soc. 39: 147.

Shankle M. W., D. R. Shaw, W. L. Kingery, M. C. Smith, and M. A. Locke. 1998. Fluometuron adsorption to riparian forest soil. Weed Sci.12: 58.

Shankle M. W., D. R. Shaw, W. L. Kingery, M. Boyette, C. R. Medlin. 1999. Fluometuron degradation in field capacity and saturated soil from a riparian forest epipedon. Proc. North Cent. Weed Sci. Soc. 39: 145-146.

Strek, H. J., J. J. Dulka, and A. J. Parsells. 1995. Humic matter content vs. organic matter content for making herbicide recommendations. Proc. South. Weed Sci. Soc. 33: 1984-1995.

Suwaketnikom, K., and R. Sattayanikom. 1991. Efficacy of s-atrazines as influenced by adsorption and mobility of various soils. Kasetsart Jounal: Natural Sciences Thailand. 25: 477-483.

Taylor, K. L. 1998. The effect of previous year's seed production on herbicide efficacy. Thesis, Iowa State University, Ames.

Teske, M. E., J. W. Barry and H. W. Thistle Jr. 1996. "FSCBG Predictions Coupled to GPS/GIS Aircraft Tracking," Pesticide Formulations and Application Systems: 15th volume, ASTM STP 1268, American Society of Testing Materials.

Wallace, A. 1994. High-precision agriculture is an excellent tool for conservation of natural resources. Commun. Soil Sci. Plant Anal. 25: 45-49.

Warner, J. E., D. A. McWilliams, and A. F. Wiese. 1990. Weed Sci. 210: 93.

Winkle, M. E., J. R. C. Leavitt, and O. C. Burnside. 1981. Effects of weed density on herbicide absorption and bioactivity. Weed Sci. 29: 405-409.

ACKNOWLEDGEMENTS

I would like to thank Bruce Battles for helping me in many ways while undertaking this study. Many thanks go to my co-major professor Dr. Robert Hartzler for providing me the opportunity and for having the patience to see me through this research, and for providing the funding as well as a graduate research assistantship to conduct this study. I developed skills for conducting research—more than I could ever imagine. I am also grateful to Dr. Russell Mullen, also my co-major professor, for providing me with a graduate teaching assistantship to conduct this research. Thank you Dr. James Baker and Dr. Mark Gleason for your active roles as committee members.